



Ecosystems and Climate Change *Research Priorities for the U.S. Climate Change Science Program*

Recommendations from the Scientific Community



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U.S. CLIMATE CHANGE SCIENCE PROGRAM

Ecosystems and Climate Change
Research Priorities for the
U.S. Climate Change Science Program
Recommendations from the Scientific Community

Report on an Ecosystems Workshop

Prepared for

the Ecosystems Interagency Working Group

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INTRODUCTION

In 2003, the Ecosystems Interagency Working Group (EIWG) of the U.S. Climate Change Science Program (CCSP) convened a small group of scientists¹ to plan a workshop and encourage participation by leading ecologists and resource managers in the public and private sectors. The goal of the workshop was to identify critical research needs that address the complex linkages and feedbacks between climate and ecological systems.² The Ecosystems and Climate Change workshop was held in 2004³ in Silver Spring, MD, and was attended by over 100 participants.⁴

Here we summarize and interpret the workshop discussions and outcomes with a focus on the key research needs that were identified within each of three areas:

1. *Feedbacks between ecological systems and global change*
2. *Consequences of global change for ecological systems*
3. *Sustaining and improving ecological systems in the face of global change*

By self-selection, workshop participants divided into three groups—one for each of the three research areas. Each group was asked to: (a) identify priority research questions related to its area; and (b) describe approaches to addressing the research questions. For each of the three groups, volunteers⁵ moderated the discussions and captured the essential points that came from the group discussions. They also contributed to the development of this document. Every attempt was made to represent the consensus views of the participants.⁶

We begin (Section 1) by providing some context for the report, then list the key research questions⁷ identified by each of the three groups (Section 2). Not surprisingly, there is considerable overlap in research priorities across the three sets of questions. Recurring priorities, such as ecosystem disturbance, timing of ecological processes, and biodiversity are discussed in Section 3. We close by discussing cross-cutting issues relevant to all of the priority research topics (Section 4) and by identifying several ecosystem types that merit special consideration in setting CCSP research priorities (Section 5).

¹ Francisco Chavez (Monterey Bay Aquarium Research Institute), Alan Lucier (National Council for Air and Stream Improvement), Harold Mooney (Stanford University), Margaret Palmer (University of Maryland), and William Schlesinger (Duke University).

² See Appendix 1 for an overview of past research on ecosystems and global change.

³ See Appendix 2 for the workshop agenda.

⁴ See Appendix 3 for the list of participants and their affiliations.

⁵ See Appendix 4 for group leaders, moderators, and recorders.

⁶ The writing team relied heavily on ideas expressed by the participants and thank those who wrote phrases and sentences that were captured in the session notes and incorporated in this section. We accept responsibility for the synthesis and interpretations presented here, and apologize for errors of omission and commission.

⁷ Critical research questions that were identified by each group are presented in this report after only minor editing for grammar and clarity. One research question (#1.8) was added after the workshop in response to comments on a public review draft of this report.

Section 1

BACKGROUND AND CONTEXT FOR RESEARCH

Scientific concern about global change is driven by potential negative impacts on human societies and the ecosystems that sustain them. We all depend directly or indirectly on the products and services provided by ecosystems—for example, crops, livestock, fish, wood, clean water, oxygen, and wildlife. An important role of science is to provide society with accurate information on the probability that global change will have impacts on ecosystems, where impacts are most likely to occur, why they occur, and what can be done to prevent, minimize, or repair the damage they cause.

Ecosystem science deals with the complex interactions between living organisms and their environment, particularly interconnections that allow organisms to change the physical and chemical properties of their environment. These interconnections involve ‘feedbacks’ when a change in environmental conditions affects organisms and ecosystems in ways that cause further changes in the environment. Interactions that amplify environmental changes are called positive feedbacks, whereas interactions that suppress changes are called negative feedbacks. For example, sunlight heating the ocean causes water to evaporate and form clouds, which blocks sunlight and cools the ocean, thereby leading to a negative feedback. In contrast, cold weather can allow snow to cover the ground, which reflects sunlight back into the atmosphere and causes temperatures to get colder, leading to a positive feedback on air temperature. Plants and animals can interact with these physical processes to strengthen or weaken either positive or negative feedbacks. Fortunately, in healthy ecosystems, most ecological processes involve negative feedbacks, which function to stabilize ecosystems. It is not yet clear, however, how much of this stabilizing function has been lost, given the large number of ecosystems globally that are already heavily influenced by human activities.

The consequences of global change for human societies are complex. Some regions and activities will benefit from global changes that are already occurring, while other regions may be negatively impacted by the same changes. Societies can likely adjust to many of the anticipated effects of global change, and scientific research can help identify effective ways to adjust. One of the greatest concerns of scientists is the possibility that global changes could produce positive feedbacks that cause environmental conditions to worsen and threaten the physical and economic health of our society, or that changes will be too rapid for organisms to adapt and thus result in large abrupt changes in ecosystem states. It is the responsibility of scientists to identify the most serious problems that could occur, to determine the probability or risk that they actually will occur, and to identify the most cost-effective ways to reduce the risk of occurrence. Without this information, society cannot rationally assess the costs and benefits of policy options.

The research priorities identified in this report by ecosystem scientists relate directly to the most critical needs of society: food from the land and water; abundant, clean fresh water for consumption, industry, agriculture, recreation, and flow to coastal waters; clean air that minimizes health risks to humans and risks to ecosystems; healthy and productive estuaries and oceans bordering coastal regions where over half of all U.S. citizens live; security from diseases

and environmental disasters; a healthy environment for recreation and enjoyment of nature; and wildlife and biodiversity.

The strategic plan developed by the CCSP stipulates that their ecosystems research program should: build enhanced capability to forecast impacts of multiple environmental changes; focus on economically important ecosystems, and regions or ecosystems that will likely experience abrupt environmental changes or threshold effects; consider a 50-year time horizon; and consider how to maintain ecosystem goods and services at current levels under global change.

There was broad support for these concepts at the workshop, with the caveat that some ecosystem responses to global change will be either incomplete or ongoing 50 years from now, and that the rate of global change may accelerate during this time horizon and thereby lead to greater effects on ecosystems than presently exist. These concepts were discussed by some workshop participants as ‘boundary conditions’ for approaching the research questions. It is recommended that CCSP incorporate these boundary conditions in future requests for proposals addressing ecosystems research questions.

Several recurring themes in workshop discussions of research approaches were consistent with ideas expressed in the CCSP Strategic Plan. These recurring themes include strong recommendations to:

- Strengthen and expand systems for monitoring climate, air and water quality, atmospheric deposition, species, plant communities, and disturbance processes.
- Develop and deploy networks of observation systems (e.g., AmeriFlux, IOOS, ORION, NSF’s proposed NEON network) to gain quantitative understanding of ecosystem processes in representative systems and across gradients of land use and climate (Figure 1).
- Conduct large-scale experiments to test key hypotheses about ecosystem responses to changes in global change factors.
- Use models to formulate testable hypotheses, forecast change, inform research priorities, and integrate information from monitoring systems, observation networks, and experiments.
- Communicate results and uncertainties in formats useful and accessible to policy makers and resource managers.

Figure 1. One of the sampling buoys used by scientists to gather data on water chemistry, temperature, and climate as part of long-term research on the ecological impacts of climate change. Photo courtesy: the North Temperate Lakes Long-Term Ecological Research Project, T. Kratz.



Section 2

CRITICAL RESEARCH QUESTIONS

Area 1. Feedbacks between ecological systems and global change

- 1.1 Climate change will likely alter the frequency and severity of episodic disturbance events (e.g., wildfire, floods, drought, storm surges, El Niño, insect outbreaks, pathogens). Will such disturbance regimes interact with resource management and biological characteristics to modify energy, water, and trace gas fluxes of aquatic and terrestrial ecosystems sufficiently to alter climate or other ecosystems? How are these interactions and subsequent effects expected to vary across gradients of land use (i.e., from unmanaged to managed or urban ecosystems) and ecosystem types (e.g., terrestrial, aquatic, oceanic)?
- 1.2 How do large perturbations of regional and global N cycles influence greenhouse gas exchanges and feedback to climate?
- 1.3 What are the carbon and trace gas feedbacks that result from the influence that global change has on soil, aquatic sediments, and poorly aerated environments?
- 1.4 If global change affects biological diversity (including species diversity and genetic diversity), species extinctions, invasive species, and species composition, how do these effects feedback to climate through alterations in water balance, transpiration, albedo, carbon cycling or trace fluxes? At what scale?
- 1.5 Since phenological changes in primary and secondary production may be associated with global change, but may be variable and unpredictable, how will these affect surface fluxes and feedbacks to climate?
- 1.6 What are the feedbacks to climate from changes in stomatal conductance, canopy growth and architecture, and canopy albedo?
- 1.7 What are the magnitudes of the feedbacks to climate attributable to ongoing changes in albedo, trace gas fluxes, and aerosols in tropical, arid, and high latitude ecosystems? How might these feedbacks be affected by future responses of these ecosystems to climate change?
- 1.8 In many areas, sea level rise and/or a reduction of freshwater flows will lead to the spread of drought- and salt-resistant fauna and flora in riparian and coastal zones. What are the form and magnitude of potential feedbacks to climate, global gas exchanges, and water availability?

Area 2. Consequences of global change for ecological systems

- 2.1 How do changes in temperature, tropospheric chemistry (including CO₂, O₃, NO_x), and precipitation directly affect carbon, water, and nutrient cycles, and indirectly affect these ecosystem cycles by altering the frequency and intensity of biotic outbreaks, pests, and disease? Are such effects more pronounced in human-dominated or intensively managed ecosystems? Are alterations to the water cycle (e.g., stores and fluxes of ground water) associated with the spread of pathogens and disease?
- 2.2 How does global change alter nutrient and organic matter inputs to soils and aquatic (marine and freshwater) ecosystems, and in turn, the structure and function of their biotic communities? What are the consequences for productivity, nutrient retention or loss, and carbon sequestration?
- 2.3 How do changes in the global water cycle that will increase the variability in soil moisture of upland ecosystems and runoff to aquatic ecosystems influence community structure and ecosystem processes along a gradient of managed to unmanaged landscapes? How will changes in freshwater inputs affect the coastal oceans?
- 2.4 How do climate-driven changes in the duration and timing of biological processes affect growth and survival of pests and pathogens, ecosystem productivity, energy and nutrient exchanges, and sensitivity of species and ecosystems to climatic extremes (e.g., late frosts, early plankton blooms) (Figure 2)?
- 2.5 What attributes (e.g., life histories) influence the vulnerability of biodiversity and community structure to climate-induced changes, and do anthropogenic factors enhance or mitigate this vulnerability?
- 2.6 Which ecosystems (e.g., wetlands, high altitude forests) or ecosystem properties (e.g., low diversity systems, highly modified systems) are more vulnerable to abrupt and dramatic state changes in response to climate change? What are the determinants of these changes, both climatic and ecological? What system properties can be used to forecast the probability that systems may recover (resiliency)?
- 2.7 How do climate-induced changes in the frequency and intensity of disturbance events (e.g., wildfire, floods, drought, insect outbreaks, and storm surges) affect the ability of ecosystems to provide goods and services, and how do land use or human activities exacerbate or mitigate this?
- 2.8 How do climate-induced changes in hydrographic structure and circulation (e.g., stratification, thermal regimes, and current patterns) influence the structure and function of ocean and lake food webs, and the productivity of ocean and lake resources?

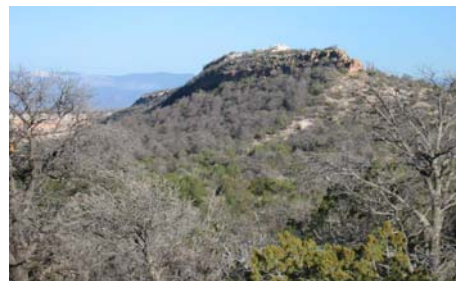


Figure 2. Pinyon pine mortality associated with Pinyon Ips beetles (*Ips confusus*) in the Jemez Mountains, New Mexico, March 2004. Photo: Craig D. Allen, U.S. Geologic Survey.

Area 3. Sustaining and improving ecological systems in the face of global change

- 3.1 In the face of global change and multiple natural resource management objectives, how are tradeoffs among ecological goods and services to be evaluated? How do we incorporate uncertainty and margin of safety into multi-objective management? For example, how do we consider resilience to climate change and greenhouse gas mitigation as additional objective functions?
- 3.2 What are the ecological impacts of ecosystem management options for mitigating climate change, such as renewable energy and carbon sequestration?
- 3.3 Given that roughly half of the U.S. population lives within coastal zones, what strategies can be implemented to preserve ecosystem goods and services in these zones? How can coastal managers and inhabitants use integrated information about global climate change and other environmental issues (Figure 3)?
- 3.4 How do we develop knowledge of multiple sources and scales of ecosystem change to design appropriate management strategies?
- 3.5 How does scientific understanding influence public perception and subsequent feedback to ecosystem management? How do we develop information delivery and decision support systems to provide managers and the public with up-to-date information and tools about global change to design successful management strategies?
- 3.6 How do we describe the status of major ecosystems at multiple spatial scales meaningfully to management and the general public? These descriptions should include key state and flux variables (such as NPP, standing biomass, biodiversity, turnover rates, and species composition) as well as how to measure and express trends resulting from management and global change. These metrics could include easily observable stores, fluxes, residence times, and community structure.
- 3.7 Can we design new ecosystems, or either relocate or restore existing ecosystems to meet local to national needs, and to adapt to climate change while providing essential ecosystem services?
- 3.8 How do we conserve the genetic foundations of major ecosystems that are responding to global changes? For example, how do we design and manage ecosystem reserves and gene banks to be effective in genetic conservation?



Figure 3. Watermen on opening day at a harvest reserve in the Chesapeake Bay. Watermen are allowed in the reserves at certain times of the year. Photo: Ken Paynter.

Section 3

RESEARCH PRIORITIES AND APPROACHES SUGGESTED BY WORKSHOP PARTICIPANTS

Ecosystem processes

A central recurring theme at the Ecosystems Workshop was the need to develop better mechanistic understandings of ecosystem processes, including interactions of ecosystems with the atmosphere, climate, and human activities. Better mechanistic understandings of such processes will increase our confidence in predictions of ecosystem responses and feedbacks to global changes.

Workshop participants identified and discussed several priority topics related to ecosystem processes that merit further investigation. Priorities include:

Disturbance and recovery

The ecological research community has made considerable progress in developing mechanistic understandings of ecosystem responses to, and recoveries from, disturbances. Research has not yet, however, addressed comprehensively the ecosystem impacts of changes in the frequencies and intensities of disturbance regimes that may result from global changes.

Changes in the frequency and intensity of disturbances can alter ecosystem dynamics and could create new environmental conditions that influence feedbacks of energy and greenhouse gases to the atmosphere and the climate system. Interactions among disturbance types or agents are important considerations in many systems. For example, episodes of cohort senescence and mortality in lodgepole pine forests in the western United States are attributable to interactions among stand ageing, drought, and pine beetle outbreaks. Increases in wildfires resulting from episodes of cohort senescence in these systems can decrease carbon storage and increase carbon dioxide and trace gas emissions to the atmosphere, thereby feeding back to the climate system (Figure 4). Soil erosion in the aftermath of wildfires can have significant effects on forest regeneration and ecosystem recovery. On the other hand, indirect effects of fire via the stimulation of nitrogen-fixing vegetation can actually contribute to longer-term increases in ecosystem nitrogen and carbon stocks.



Figure 4. Ecosystem disturbance, such as fire, can have significant effects on carbon storage capacity, gas emissions to the atmosphere, and soil erosion. Photo: John McColgan, BLM, Alaska Fire Service.

Extreme events, such as hurricanes, floods, and severe droughts, can cause major ecosystem disturbances that impose huge burdens in terms of economic costs and human suffering and death. There is a need for research on the potential for increases in the frequency and intensity of extreme events in response to climate change, development patterns, and other interacting factors. Understanding interactions between climate changes and landscape alteration is critical for minimizing the impact and probability of a range of disturbance types. For example, Hurricane Katrina caused tremendous human suffering, destruction of property, degradation of sensitive ecosystems, and environmental contamination. To what extent were the impacts of this storm linked to prior loss of wetland ecosystems, and can we expect an increase in the frequency and severity of such disasters as land is developed and the climate continues to change?

Some ecosystems respond dramatically and abruptly to climate changes that fundamentally alter community structure and ecosystem function and lead to changes in ecosystem states. Important questions for CCSP include:

- Which ecosystems are particularly vulnerable to such state changes?
- What climatic and ecological factors drive these changes?
- What system attributes can be used to forecast the probability that ecosystems will recover functioning following major changes in state?

A priority for CCSP is to strengthen and expand the capability of ecosystem monitoring and observing systems to collect, quantify, and distribute information about ecosystem disturbances (types, intensities, and frequencies), including potential state changes. An important task is developing better approaches for integrating remote sensing and ground-based observations. Another challenge is establishing more extensive networks of sensors for collecting data on drivers of disturbance, particularly in remote locations, in extreme environments with low human populations, or in environments that are extremely important in the provisioning of critical ecosystem services (e.g., coastal and riparian wetlands, headwater streams). Drivers of disturbance include ocean temperature and circulation patterns, climate variables, soil moisture, atmospheric carbon dioxide and ozone concentrations, atmospheric deposition of nitrogen and other compounds, land clearing and/or impervious cover, and biological drivers of disturbance, such as insects and pathogens (Figure 5).

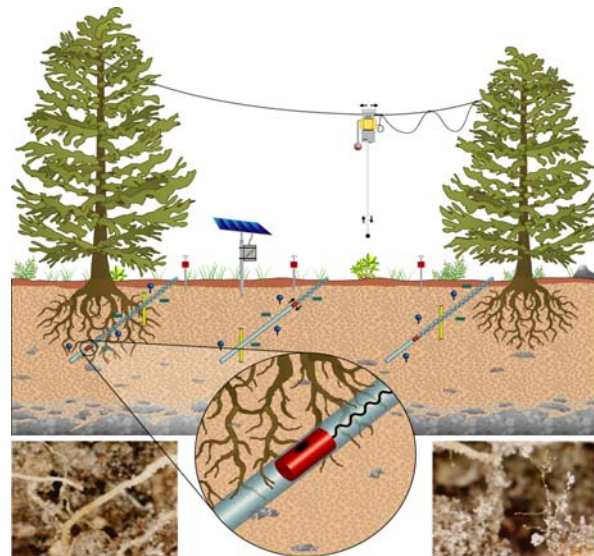


Figure 5. Tracking changes in ecological patterns and processes is increasingly going to rely on the use of networks of sensors deployed across the landscape. Here, sensor arrays are in place to detect changes in soil moisture, soil respiration, evapotranspiration, and the movement of materials between roots, fungi, and soil that may be associated with changes in air temperature, humidity, and rainfall. Center for Embedded Networked Sensing, UCLA. Graphics by Jason Fisher.

In addition to observations, there is a need for integrated, large-scale experiments capable of testing hypotheses about causes of disturbance, their impacts on ecosystem dynamics, and their feedbacks to the climate system. Examples include watershed-scale manipulations of disturbance regimes, experiments in which CO₂ and ozone concentrations are increased over large areas, and large water parcel manipulations (e.g., IRONEX in the Pacific Ocean).

Models have critical roles in integrating information across spatial and temporal scales and in assessing the sensitivities of different ecosystems to perturbations by multiple factors. Priorities for model development include:

- Down-scaled climate models, including models that incorporate snowpack and hydrologic (surface and sub-surface) dynamics, meso- and finer-scale ocean circulation, fire dynamics, and regional topography.
- Models that couple physiological and soil processes with ecosystem energy, water, trace gas, carbon dioxide, and aerosol exchanges.
- Surface models which incorporate various types of landscape disturbances and land management activities to enable estimation of ecosystem feedbacks to the atmosphere at large scales.
- Models of ecosystem and human population responses to extreme events, including effects of past and ongoing development on ecosystem vulnerability/resilience.
- Models that combine biophysical and biogeochemical drivers with population dynamics to predict ecosystem responses to disturbance.

Outcomes of these activities and analyses should be incorporated into decision support systems that integrate energy, water, and trace gas fluxes within management decision frameworks. Resultant decision support systems should be used to integrate probabilities of disturbance events from climate change scenarios into management decisions.

Role of primary producers in regulating energy, water, and greenhouse gas exchanges between ecosystems and the atmosphere

Ecosystems and the atmosphere are tightly coupled through biophysical and atmospheric processes with rapid feedbacks (i.e., minutes to hours) involving fluxes of energy and matter. Ecosystem surfaces have complex biophysical properties influenced by factors such as energy inputs (long- and short-wave radiation), surface reflectance/absorbance characteristics, surface roughness, and genetic/ecophysiological controls on metabolism.

Primary producers have important roles in regulating exchanges of energy and matter between ecosystems and the atmosphere. Quantifying plant and algal-mediated exchanges of matter and energy between ecosystems and the atmosphere is a critical challenge for the CCSP. An important aspect of this challenge is estimating effects of global change factors and ecosystem

management options on plant and algal-mediated exchanges. Global change factors of interest include tropospheric carbon dioxide and ozone concentrations, nitrogen deposition, changes in temperature and precipitation, and impacts of land use activities such as agricultural and urban development. These factors (and their interactions) can influence the community structure and function of primary producers in terrestrial and aquatic ecosystems at time-scales ranging from minutes to centuries.⁸ Important measures of community structure and function include biomass, plant evapotranspiration, community growth and architecture, and surface albedo.

Manipulative experiments designed to alter ambient CO₂, N inputs, and land management should be conducted to better understand the effects of these factors on primary producers (including algae and terrestrial plant canopy growth, architecture and temperature), evapotranspiration, water balance, and trace gas emissions. Measurements of response variables are needed at scales ranging from individual leaves to whole canopies. A network needs to be developed to collect, compile, and make available water and energy exchange studies from a variety of ecosystems.

Remotely sensed data on spatial patterns of leaf chemistry, plant canopy structure, and oceanic primary production can provide additional information about effects of ecosystem structure on water and energy exchanges. Influences of spatial and temporal variability on land surface and water feedbacks need to be investigated through a combination of observations and modeling. Workshop participants highlighted needs for natural and manipulative experiments relating species diversity and composition to ecosystems functioning (e.g., water balance, transpiration, albedo, carbon and nutrient cycling, and trace gas fluxes). Effects of natural disturbance and land use practices need to be incorporated into models of water and energy exchange.

Remote sensing from satellite- and aircraft-based sensors has provided information for detecting changes in land surface and ecosystem properties at low and high latitudes. Process-level studies on the effects of changes in land use and climate drivers have provided a great deal of mechanistic understanding of ecosystem responses to individual drivers (Figure 6). However, predictions of ecosystem- and biome-scale responses at decadal and

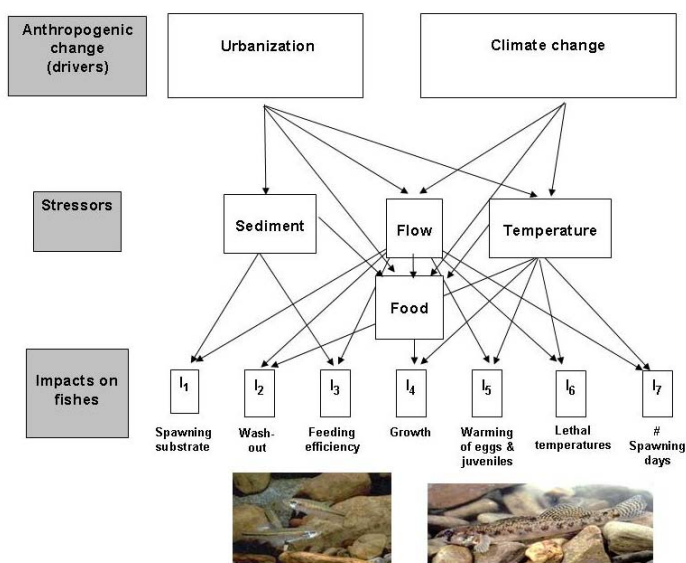


Figure 6. Urbanization is increasing dramatically worldwide. It is well known to influence flow, temperature, and sediment inputs to streams. Over the next 30–50 years, the impacts of urbanization may be more pronounced in some regions due to interactive effects with a warmer and potentially wetter climate. This is expected to lead to local fish extinctions or replacements. Credit: Karen Nelson and Margaret Palmer.

⁸ Workshop participants noted that data from tower flux sites will be useful in evaluating water and energy exchanges at leaf, canopy, and regional scales. It was also noted, however, that full energy closure at tower flux sites is seldom, if ever, attained (at least so far).

longer time-scales will require a large-scale sensing system designed to provide information on gas exchange, plant cover and algal type, soil moisture active depth, groundwater levels, and hydrological and oceanic dynamics. This is a particular challenge in sparsely populated arctic and arid regions, and in large underdeveloped tropical regions where scientific infrastructure is poorly developed. Predictions of the magnitudes and durations of positive feedbacks from these systems will require mechanistic and spatial modeling efforts coupled with natural experiments and manipulative experiments designed to simulate effects of multiple global change drivers.

Timing of ecological processes

Timing is critical in biological and ecological processes. Organisms must adapt their growth period or life cycle to the length of time during which environmental conditions are suitable for growth. Climate change can disrupt evolved relationships between organisms' life cycles and seasonal cycles of climatic conditions by lengthening or shortening the growing season, or by changing its timing in relation to cues that organisms use to regulate their life cycle, such as day length, air or water temperature, or changes in salinity or ice cover. Mismatches in the timing of growth or reproduction in relation to the availability of critical resources such as food or nutrients can influence ecosystem productivity, energy and nutrient flows, sensitive life stages and behaviors of organisms, and the distributions and interactions of species, including predator-prey and pathogen-host relationships.

Several needs in this area were recognized by the participants. Several existing networks monitor phenology at the species level. These networks provide valuable information on the timing of processes such as leaf out, flowering, heading of grains, molting of insects, and development of plankton blooms. Phenology networks should be sustained, strengthened, and more fully utilized. An important challenge is to develop an integrated picture of changes in terrestrial and marine phenology by linking ground-based or ship-based phenology observations with information from remote sensing platforms, climate monitoring networks, isotope analyses, and other data sources.

- Experimental studies to define phenological responses to climate and environmental influences are being conducted at several locations; there is a need to link these sites together through data sharing arrangements and development of consistent data collection protocols. There is also a need to link results of phenological experiments with ecosystem functions by using isotopic networks such as BASINS.
- Observational and experimental studies need to be better integrated with modeling studies. Current models of environmental influences on phenology emphasize interactions of day length and cumulative degree-days. There is a need to test current models against observations and with experiments. Additional modeling priorities include:
 - Develop and test models of phenological responses to disturbances such as fire, hurricanes, and insect outbreaks.
 - Continue development and testing of biogeochemical models that link phenology and/or growing season length with physiological processes (e.g., photosynthesis), evapotranspiration, and energy balance.

Organic matter inputs to soils and aquatic sediments

Many animal- or microbe-dominated environments (e.g., marine intertidal zones or coastal bays, ocean and lake bottoms, many streams and rivers, and all soils) depend on inputs of organic matter and nutrients from other systems to support their productivity and biodiversity. Such systems have critical roles in sustaining ecosystem services such as food production, carbon sequestration, water purification, water flow regulation, and habitat support (Figure 7).



Figure 7. Organic matter inputs to streams, such as wood and leaves, fuel food webs from microbes to invertebrates to fish. Photo: Margaret Palmer.

Land use activities, hydrologic alterations, climate change, elevated CO₂ concentrations, and other factors can alter the quality and quantity of organic matter inputs to these systems. Changes in the amount or timing of organic matter inputs can have major effects on productivity, diversity, and ecosystem processes. Currently, we have only limited understanding of how climate changes will alter the quality, quantity, and timing of nutrient and organic matter inputs, the structure and function of soil and sediment biota, or the roles of specific animals or microbial populations in organic matter decomposition and nutrient cycling.

Several research priorities and approaches related to organic matter inputs were suggested at the workshop.

- **Sensor development.** Develop new sensors and techniques for *in situ* (high frequency, spatially extensive) measurement of soil and sediment chemistry, biotic structure, and microbial processes (including eddy correlation techniques to monitor fluxes to air or water from soils and sediments).
- **Technique development.** Develop or adapt genomic and proteomic approaches to study the functional structure and activity of microbial communities in soils and sediments (includes training in new techniques).
- **Long-term field experiments.** Conduct whole system experiments that alter the quantity and quality of nutrient and organic matter inputs to soils and aquatic systems, and measure the effects on system structure and function.
- **Monitoring networks.** Establish a network of representative terrestrial and aquatic systems in different biomes (e.g., forest, grassland, arid land soils, headwater streams, lakes, coastal

systems) and across gradients of land use to monitor quality and quantity of organic matter inputs (and subsequent effects on decomposition and nutrient cycling) in relation to inter-annual climate variation and long-term climate change.

- **Observatories.** Expand networks of environmental observatories for belowground and sediment processes (e.g., by leveraging AmeriFlux, LTER, FACE, and coastal observatories now focused on aboveground or water column processes).
- **Sample archives.** Develop long-term and spatially expansive archival collections of soil and sediment samples.
- **Models.** Develop the next generation of mechanistic models to predict responses by soil and sediment biota to changes in nutrient and organic matter inputs.

Organic matter decomposition

Aquatic sediments and the surface layers of soils contain at least 2.5 times more C than exists in either the Earth's vegetation or the atmosphere. The metabolism of organisms in soils and sediments and associated transformations of organic matter regulate the direction and magnitude of CO₂ and trace gas exchanges between ecosystems and the atmosphere.

Although the mechanisms that produce and consume CO₂ and other greenhouse gases are well understood, our ability to measure fluxes at scales greater than that of small field plots is limited. Therefore, even the direct effects of changes in single global change drivers (temperature, moisture, various physical disturbances) on soil-atmosphere gas exchange are difficult to quantify at large spatial and temporal scales. The effects of changes in multiple drivers are even less predictable than are the direct effects of changes in single drivers. As previously stated, organic matter balances and biogenic gas exchanges are also likely to be influenced indirectly by variations in the quality and quantity of plant residues entering soils and sediments that result from any changes in primary production due to global change.

There is a need to develop capacity to predict how changes in subsurface temperature and moisture regimes, and changes in inputs from primary producers to soils and sediments interact to regulate CO₂, methane, nitrous oxide, and other greenhouse gas exchanges. Studies will be required for a range of soil types varying in their capacity to protect and stabilize soil organic matter against decomposition. Priority should be given to high carbon systems that may be subject to changes from frozen to thawed or from anaerobic to aerobic conditions. Existing knowledge of controls on individual processes should be applied to developing strategies for determining how multiple drivers interact at large spatial (10s–100s km) and time-scales (decades and longer) to: (a) influence organic matter storage in soils and sediments; and (b) regulate CO₂ and greenhouse gas exchanges among soils, sediments, and the atmosphere. Priority attention should be given to headwaters and wetlands, particularly those that occupy extensive areas at high latitudes (arctic tundra and boreal forest) where thermal and hydrologic regimes are changing and where plant cover types may be shifting due to shrub encroachment or poleward migration of treelines. These systems are of particular interest because of their large

carbon stores, which may be sensitive to warming and drying, and because the balance between methane production and consumption is strongly influenced by hydrologic status and plant cover type.

Forest ecosystems, particularly in regions now functioning as sinks for atmospheric CO₂, should also be a focus of soil carbon and gas exchange studies. Studies are needed in these regions to characterize the role of soil processes (vs. plant growth) in contributing to the CO₂ sources and sinks, and to predict the duration and magnitude of these sources or sinks. Agro-ecosystems are also a priority as current research indicates farming and cropping practices can be manipulated to maximize carbon retention and to minimize greenhouse gas emissions from agricultural landscapes. Research should also focus on sediments in lake, riverine, and estuarine ecosystems receiving high inputs of dissolved carbon and nitrogen from agricultural and densely populated landscapes. Sediments in these ecosystems can store carbon and nitrogen as organic matter, or release them as greenhouse gases, depending on variations in loading, salinity, and various global change drivers.

Systematic observations and measurements of organic matter storage in soils and sediments should be coupled with large-scale measurements of trace gas exchanges between the atmosphere and soil-sediment surfaces in the ecosystem types listed above. Ideally, these measurements would be conducted systematically across landscapes and within the context of large-scale and long-term experiments designed to manipulate global change drivers alone and in various combinations.

An important function of systematic measurements and large-scale experiments is to provide a strong empirical basis for development, testing, and improvement of models for extrapolation to regional and global scales. Modeling objectives should be considered explicitly when designing measurement programs and large-scale experiments. For example, having an objective to model organic matter storage in soils and sediments would suggest a need to measure both nitrogen and organic matter because carbon storage is often constrained by nitrogen supply.

Elevated nitrogen inputs to ecosystems

Inputs of reactive nitrogen (N_r, nitrogen oxides, and reduced N forms such as ammonium) to ecosystems are increasing globally. In the last decade of the 20th century, human-derived inputs of N_r to the Earth's ecosystems began to exceed inputs from all natural processes combined. Presently, the rate of increase in anthropogenic N_r inputs is accelerating. Research has shown that elevated N_r inputs alter key metabolic processes (primary production, decomposition, evapotranspiration) which feed back to influence climate by regulating ecosystem carbon storage and biosphere-atmosphere exchanges of energy, water vapor, carbon dioxide, methane, nitrogen oxides, and biogenic hydrocarbons (Figure 8). A comprehensive and quantitative understanding of the magnitudes of the feedbacks to the atmosphere from ecosystems subjected to elevated N_r inputs, however, is lacking. Moreover, the direction and magnitude of the alterations in ecosystem processes due to elevated N_r inputs can be modified by other global change drivers, including increased tropospheric ozone (and other air pollutants), climatic warming, poleward migration of low-latitude species, changes in growing season length, and changes in species

composition. As a result, feedbacks of energy and greenhouse gases resulting from interactions among elevated N_r impacts and other global change drivers are not yet predictable.

Presently, interactions among increasing N_r inputs to ecosystems and other climate change drivers are of most concern in industrial-agricultural regions of the northern middle latitudes where rates of fossil fuel combustion and fertilizer use are highest. High priority should be placed on research aimed at quantifying how N inputs and interacting stressors alter carbon storage and greenhouse gas exchanges in heavily impacted temperate regions. Studies should focus on intensively managed and fertilized ecosystems used for food and fiber production, and on minimally managed ecosystems in which plant growth (and possibly species composition) are strongly limited by low N availability. Knowledge gained in impacted regions should be tested in lower latitude regions now experiencing intensification of agriculture and industrial growth where N_r inputs will increase in the near future.

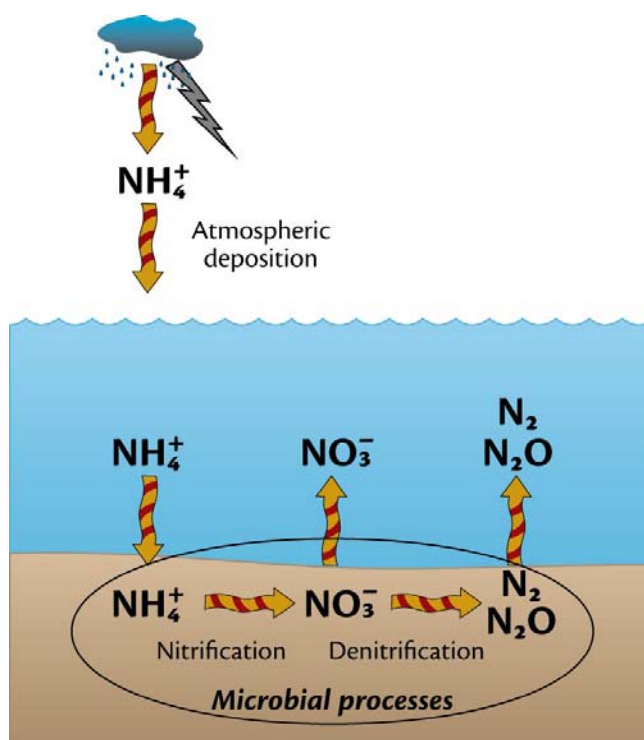


Figure 8. The ongoing increase in nitrogen deposition combined with changes in the frequency or intensity of storms may lead to significant and complex changes in basic biogeochemical processes such as microbial processing of nitrogen.

There is an urgent need for an observing system that will allow for improved sampling of N_r inputs at high spatial resolution. Systems exist (e.g., NADP) for monitoring wet deposition of inorganic N_r . However, systems for measuring dry deposition of inorganic N_r , wet and dry deposition of organic N, and uptake of gaseous N forms by plant canopies do not exist. A monitoring system that could provide high resolution data on N inputs (rates and forms) to cropped and non-cropped ecosystems would be a first step in developing predictive models of feedbacks to the climate system resulting from N_r inputs to ecosystems. Further, highly urbanized areas need to be studied since recent work suggests that N deposition on or near roads, and the subsequent movement of that N to waterways, may be considerable, yet is poorly understood.

Another need is to develop observing systems for measuring (a) N_r transfers across ecosystem boundaries (particularly land-water and riverine-estuarine) and (b) feedbacks of energy and greenhouse gases (e.g., CO_2 , methane, nitrous oxide, water vapor) from terrestrial and aquatic ecosystems. Observation systems for measuring cross-ecosystem fluxes should take advantage of and add to existing hydrologic monitoring systems. Also, observations of ecosystem-atmosphere

exchanges of energy and greenhouse gases should be made at spatial and temporal scales that match scales of measurement for N_r inputs.

Much has been learned about whole ecosystem responses to elevated N_r inputs by agronomic studies of fertilizer use and by observations of whole system responses to elevated N_r inputs done at large plot and watershed scales in forested and other ecosystem types. Measurements of plant, microbial, and herbivore community dynamics and ecosystem processes (primary productivity, nitrate leaching losses, CO_2 and trace gas exchanges) have provided a great deal of mechanistic information on biotic responses to elevated N_r inputs. The most productive of these large-scale field manipulations of nitrogen inputs and cycling have been coupled with modeling activities that have led to testable predictions of ecosystem feedbacks resulting from N deposition.

Future progress in defining ecosystem impacts and feedbacks associated with elevated N_r inputs will require large-scale field studies coupled with simulation models aimed at understanding interactions of N_r inputs with other global change factors. These other factors include climate warming, increases in atmospheric CO_2 and pollutants (particularly ozone), altered water balances, and changing patterns of land use leading to fragmentation, reforestation, and other large-scale shifts in land cover characteristics. There is also new evidence that N_r inputs near to soils and waterways in urban areas may be much higher than expected, but thus far these inputs and their impacts regionally or down stream have not been quantified. Realistic approaches will take advantage of existing large-scale experiments (e.g., FACE, paired watershed studies) and unintended manipulations (e.g., fires, droughts, Gulf of Mexico hypoxia events).

Finally, any program that deals with N inputs on a national or regional scale must deal with potential changes in nitrogen fixation, which is a major input of N to the terrestrial system, particularly in ecosystems where anthropogenic nitrogen inputs are low. Nitrogen fixation inputs are spatially variable, occurring primarily in association with symbiotic nitrogen fixers, which in turn often dominate disturbed sites. This important and chronically overlooked form of nitrogen input is therefore closely linked with the potential changes in landscape-level disturbances discussed above.

Hydrologic cycle

The hydrologic cycle has critical roles in some of the most important ecosystem feedbacks between organisms and the physical environment. Soil moisture is one of the major regulators of plant growth and the productivity of terrestrial ecosystems. At the same time, plants remove water from the soil and release it into the atmosphere where it influences climate through evaporative cooling, cloud formation, and precipitation. Water not removed by plants or evaporation moves over or through the soil into streams and rivers and, ultimately, the ocean. Thus ecosystems both respond to water availability and change water availability.

Virtually all components of global change influence the feedback between ecosystems and hydrology, including temperature, rainfall, clouds and haze, human manipulation of vegetation, impervious cover, dams and drainage systems. Past work in agriculture and forestry has resulted

in important insights into how these managed ecosystems respond to changes in soil moisture and runoff. We know far less about unmanaged ecosystems, particularly those that are important to conservation of biodiversity (e.g., tropical wetlands and headwater streams) or the provision of food and water for human consumption (mountains, rangelands, coastal areas, streams and rivers).

A critical research need is to determine how changes in the global water cycle affect hydrologic processes at the watershed scale, and how changes in hydrologic processes in watersheds influence community structure and ecosystem processes in relatively unmanaged systems such as forests, rangelands, coral reefs, estuaries, wetlands, and headwater streams. A promising approach is to develop monitoring networks and models that link variations in soil moisture and runoff to population dynamics and ecosystem processes. Experiments will be needed to test hypotheses suggested by monitoring and modeling studies.

Hydrographic structure and circulation in ocean and lake ecosystems

Ocean and lake ecosystems directly support a number of goods and services of value to the nation. Fishery harvests are directly related to biological and physical components of aquatic environments. Federally protected species, including marine mammals and sea turtles, also depend on specific components of freshwater and marine ecosystems. Further, habitats that support fisheries and protected species may be altered through changes in climate (e.g., coral reefs, seagrass). Finally, services provided by a number of federally protected areas depend on the continued function and productivity of lake and ocean ecosystems (e.g., national parks, national monuments, national wildlife refuges, national estuarine research reserves, national marine sanctuaries).

Climate change can affect these aquatic goods and services through multiple pathways. First, the structure and function of aquatic ecosystems can be altered by changes in primary production and the subsequent transfer of energy to higher trophic levels (e.g., zooplankton, fish, mammals, birds). Primary productivity and trophic structure in aquatic environments are vulnerable to changes in water-column stratification and mixing, irradiance, nutrient cycling, and resulting changes to physiological and population-level processes. Second, many aquatic species have complex life histories with multiple stages that utilize different habitats. Successful continuation of the life cycle is dependent upon a combination of planktonic transport and migration, both of which are influenced by the combination of physical and biological processes. Alteration of water currents or vertical stratification of water bodies have the potential to disconnect certain life stages from favorable habitats, which could lead to the collapse of fisheries or the displacement or collapse of animal populations, such as sea birds, whales, coastal bears, or other large predatory animals (Figure 9). In arctic and boreal regions, increased freshwater runoff from glacial melting and other sources has the potential to alter the physical and biological dynamics of high latitude oceans. These regions support the most productive fisheries on Earth and are critical sources of protein for marine wildlife as well as humans. Third, altered temperature regimes may lead to shifts in species distributions. New combinations of species will be interacting and the outcome may lead to unpredictable changes in trophic structure, population sizes, and ecosystem processes. Species that cannot migrate or compete in the new setting may be extirpated locally or even go extinct globally.

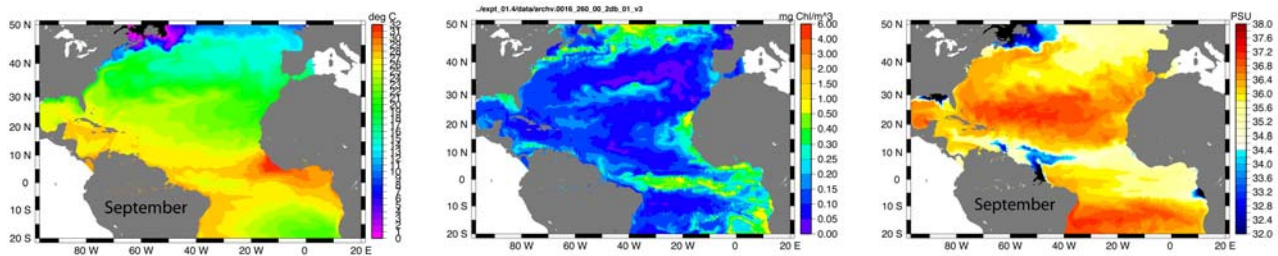


Figure 9. September sea surface temperature, surface chlorophyll, and salinity from a 0.5-degree spatial resolution ocean general circulation model (Hybrid Coordinate Ocean Model) of the Atlantic Ocean. Recent concerns about Atlantic tropical sea surface temperatures and hurricane intensification highlight the need for accurate model predictions of the tropical and western boundary current structure and their associated eddy fields. Images: Victoria Coles.

In the past several decades, we have learned much regarding how environmental variability affects fisheries and protected species in specific ecosystems. We have also made great progress in understanding the importance of habitat and the role of protected areas in promoting the sustainability of fishery resources and the conservation of protected species. An important research priority is to sustain and expand existing programs that have advanced our understanding of entire ecosystems (e.g., the IGBP's program on Global Ocean Ecosystem Dynamics, GLOBEC).

Effects of elevated CO₂ on seawater chemistry

The oceans have absorbed a substantial fraction of CO₂ released to the atmosphere by fossil fuel combustion since the beginning of the industrial revolution. Recent estimates suggest that the oceans accumulated more than 400 billion metric tons of fossil CO₂ from 1800 to 1994, i.e., ~48% of the total fossil fuel carbon released to the atmosphere during this period. The rate of ocean uptake of carbon from fossil fuel is now close to 1 million tons of CO₂ per hour.

Although the climate impacts of increasing atmospheric CO₂ levels have received great attention, the direct effects of CO₂ enrichment in the upper ocean have had relatively little discussion. Dissolution of CO₂ in water forms carbonic acid, which can dissociate to bicarbonate. Increasing atmospheric concentrations of CO₂ accelerate the rate of carbonic acid formation. This raises basic questions about impacts on ecosystems and biogeochemical cycles to which we simply do not yet have answers.

A fundamental concern is the effect of changes in water chemistry on chemical and biological processes, especially in the upper, most productive layer of the oceans. Research is needed to assess the potential for effects and feedbacks that could occur through several mechanisms, such as:

- Changes in water chemistry affect the speciation of silica in seawater, thus affecting siliceous primary producers (diatoms) with secondary impacts on food webs including fish and marine mammals.

- Changes in water chemistry affect the speciation of metals (Fe, Cd, Co, and Mn) and adsorption of metals to suspended particulate matter. Resulting changes in metallic nutrient availability affect photosynthetic and respiratory processes with complex secondary effects on ecological processes.
- The cumulative effects of changes in water chemistry on biological processes cause a feedback to the atmosphere by slowing the biological pump of CO₂ to the deep ocean.
- Changes in CO₂ levels on calcification rates by marine organisms that produce carbonate shells or skeletons have long-term implications.

Biodiversity

The genetic information represented by the Earth's biodiversity is an irreplaceable resource for medicine, agriculture, and the ability of managed and unmanaged ecosystems to respond and adapt to changing conditions. Already, human disturbances such as over-harvesting, habitat destruction, the introduction of exotic species, and the fragmentation of formerly continuous ecosystems are influencing the ability of populations to adapt to climate change (Figure 10).

Consequences of global change for biodiversity

Ecosystems research is critical in helping society anticipate and reduce the effects of global change factors on biodiversity. We need to develop the capacity to quantify population and species extinction risks over wide ranges of environmental conditions. Because of the co-evolved dependencies within some groups of species, and the importance of species that provide critical resources or habitat for other species, local extinctions or population reductions may have cascading effects that impact multiple species and affect ecosystem structure and dynamics. To improve our ability to project population responses, we need to be able to identify and quantify the intrinsic and extrinsic attributes of species in terrestrial, aquatic, and marine environments that may affect their relative vulnerabilities to climate change interacting with other important stressors.

Defining the consequences of global change for biodiversity is an enormous challenge. Workshop participants identified several specific research priorities and approaches.

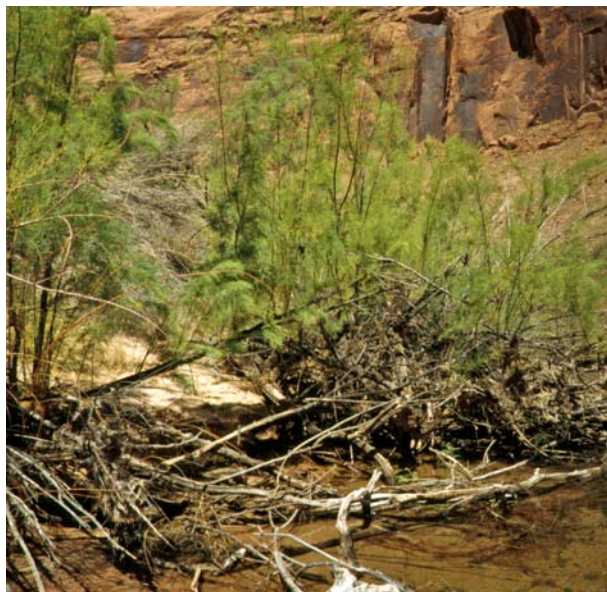


Figure 10. This invasive riparian plant species (tamarisk or 'salt cedar') was intentionally introduced in the southwest as an ornamental, but has now spread along the edges of most rivers from northern Mexico to southern Canada. It is rapidly replacing many ecologically important native species such as cottonwoods. Photo: Margaret Palmer.

- Review and integrate models that have been used to produce estimates of species extinction rates for specific taxa and regions.
- Develop better process-based models of environmental factors controlling species ranges.
- Identify species and/or life history attributes that are highly vulnerable to the effects of climate change, and for these, gather data on their distributions and habitat characteristics. Improve long-term collection and archiving of biological materials (genomic data, biotic vectors, organisms) over large spatial scales with corresponding climatic, location, and life history data.
- Digitize museum records of species distributions and map historical and current species' ranges.
- Develop observing systems to monitor genetic diversity within indicator species.

Feedbacks from biodiversity to the atmosphere

Biodiversity can have important effects on ecosystem functions, and individual species can regulate ecosystem sources of greenhouse gases (for example, beavers as they influence methane fluxes in high latitudes). This suggests an important question for CCSP: Can impacts of global change on species composition and species richness alter water balance, energy balance, and trace gas fluxes at magnitudes that alter climate at regional or global scales? These feedbacks could be either positive or negative, and likely vary from ecosystem to ecosystem. For example, changes in microbial communities could either increase or decrease trace gas fluxes from soils. Invasive plant species could alter fuel loading and hence ecosystem fire regimes and related pulse releases of CO₂, particulates, volatile organics, and NO_x to the atmosphere. Loss of top predators in marine ecosystems may fundamentally alter trophic dynamics and have cascading effects.

Observations and data integration are needed to provide a synthesis of biotic community attributes such as species diversity, species dominance, and functional types in ecosystems at 1-km-grid resolution for the country and for coastal areas. This information should be evaluated with satellite data and other large-scale environmental data types. Incorporation of sub-grid functional type distribution using TM or other fine resolution data (e.g., IKONOS data, SPOT, or plot data) is needed to capture fractional coverage of these features within coarser-scale analysis. Method development for scaling from plots to landscapes remains a major challenge.

Natural and manipulative experiments are needed to better characterize relationships among species and functional group diversity and ecosystems functioning (e.g., water balance, transpiration, albedo, carbon cycling, or trace fluxes) and ecosystem services. Linking such relationships with current and historical land use and spatial-temporal disturbance patterns will provide information for ecological forecasting of changes in ecosystem structure and services resulting from various regimes. It will also provide information critical to the potential for restored or designed ecosystems to mitigate the impacts of climate change.

Integration of functional types into biogeochemical models is also needed to facilitate the analysis of multiple stresses on ecosystem dynamics. Fully coupled biotic-biogeochemical-physical models will also provide a framework to assess biotic feedback to the climate system.

Integrating global change science into natural resource management

Describing ecosystems in terms meaningful to managers and the general public is a prerequisite for informed public discourse on global change and its ecological consequences. Priority research topics suggested by workshop participants include: (a) defining and communicating envelopes of natural variability and why this concept is critical to identifying dangerous changes in ecosystem states; (b) converting raw monitoring data into secondary data products useful to managers and public; and (c) integrating data into models for assessment and prediction.

Characterizing costs, benefits, and tradeoffs of management options

Humans have developed diverse and complex systems for managing terrestrial and aquatic resources. Proper functioning of these management systems depends on shared knowledge, compromises and other relationships among elected officials, government agencies, diverse organizations in the private sector, and individual citizens.

Introducing new objectives into resource management systems is complex and controversial to the extent that pursuit of the new objectives disrupts the pursuit of established objectives. Resistance to new objectives can be especially strong when stakeholders perceive that the benefits of pursuing the new objectives are more uncertain or less tangible than the costs. Resistance can also be strong if the benefits are not perceived as relevant locally.

A community of resource managers is more likely to integrate global change science into its management systems when key findings are presented in the context of the community's existing knowledge frameworks and decision tools. Costs, benefits, and tradeoffs involved in pursuing resource management objectives based on global change science should be characterized as completely and accurately as possible (Figure 11). Unfortunately, methods for characterizing these costs, benefits, and tradeoffs are generally lacking. Further, because of poor scientific understanding of factors that influence the resilience of ecosystems, it is hard to identify thresholds (indicators) above which system change is irreversible.

An integrated set of ecosystem case studies is the most promising approach to developing and testing methods for characterizing costs, benefits, and tradeoffs associated with proposed responses to global change. Each case study should include the following elements: (a) definition and valuation of important ecosystem goods and services; (b) definition of significant constraints on management options (e.g., regulations, land ownership patterns, etc.); (c) valuation of the magnitude of impacts and potential for irreversible change; (d) definition and valuation of potential management responses to global change; and (e) outreach to managers and other stakeholders. Case studies should assess management options using decision support systems already in use by ecosystem managers, and should provide managers with transparent and

complete characterizations of assumptions, sources of uncertainty, and potential distributions of costs and benefits among stakeholders.

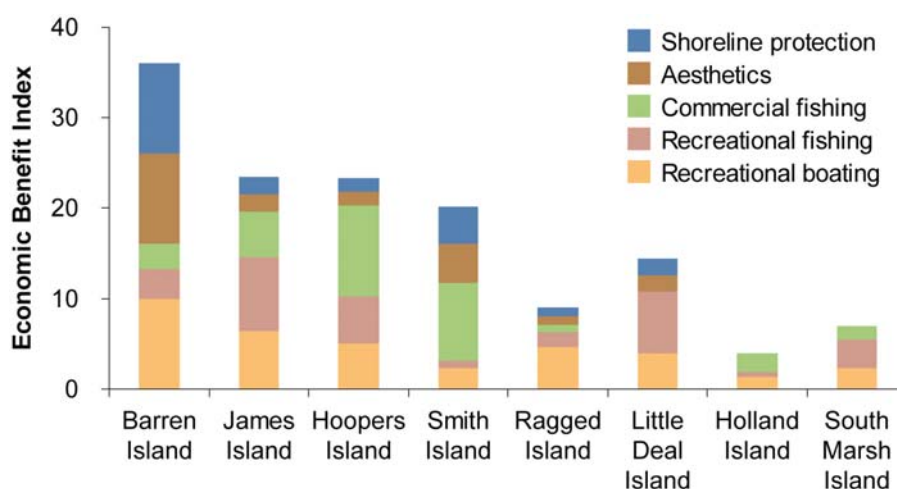


Figure 11. Research by environmental economists helps clarify tradeoffs between economic costs and environmental benefits, and helps illustrate that conserving and restoring environmental resources often generates economic benefits. This figure summarizes analysis that compares alternative Chesapeake Bay island restoration projects in terms of sets of environmental benefits that matter most to people. When combined with information about relative project costs, this information informs management and restoration decisions so as to maximize environmental benefits and minimize costs. Work by: Dennis King and Lisa Wainger.

Carbon sequestration and renewable energy production

Carbon sequestration and renewable energy production already have substantial influences on sources and sinks of greenhouse gases in the United States. Approaches for increasing carbon sequestration and/or renewable energy production are technologically feasible and potentially cost effective relative to some other options for controlling greenhouse gases. However, the ecological implications of these approaches are not well defined. The CCSP should collaborate with CCTI to investigate the ecological costs and benefits associated with the most promising options for increasing carbon sequestration and/or renewable energy production.

Section 4

CROSS-CUTTING RESEARCH ISSUES RELATED TO ECOSYSTEM RESPONSES AND FEEDBACKS

While specific types of global change impacts are known to be most probable in certain ecosystems, there are critical technical and conceptual issues that limit our ability to understand processes and predict impacts and feedbacks. Fundamental scientific advances are needed in three areas that are relevant across all ecosystems: 1) predicting the probability of catastrophic impacts and strong positive feedbacks; 2) using experiments and observations to understand the effect of multiple, interacting environmental conditions on ecological processes; and 3) dealing with spatial and temporal heterogeneity in measurements and models.

Predicting the probability of catastrophic impacts and strong positive feedbacks

While many global change processes are sometimes difficult to detect, it is now known from analysis of trace gases and isotopic ratios in ancient ice cores that sudden (within a decade) extreme climatic shifts have occurred multiple times over the past several hundred thousand years. If such sudden changes were to occur now, the consequences could be catastrophic for humans in major portions of the globe. The processes that cause sudden shifts from gradual to extreme changes are not known, although there are hypotheses suggesting that such changes could occur in many different types of ecosystems for completely different reasons. Some of these changes could involve ‘runaway’ positive feedbacks, while others could reflect the extreme range of natural variability. It is critical that society be provided accurate information to assess the risk of such catastrophic changes, and knowledge about how to reduce the risk of such changes occurring.

Multiple, interacting, simultaneously varying conditions

Scientific experiments typically examine the effects of a single factor, such as temperature, while holding all other factors constant. Unfortunately, the required caveat “all other things being equal,” simply does not apply to ecosystems, atmospheric dynamics, or global biogeochemical processes. Understanding and predicting the consequences of processes operating at regional and global scales requires knowledge of how multiple processes interact with one another within the context of multiple environmental conditions that may vary simultaneously and independently. Such knowledge is essential for predicting the ecosystem consequences of alternative climate scenarios, but currently available scientific tools and analytical methods are not capable of solving this complex problem of multiple interacting factors. New combinations of observational and experimental approaches must be developed, along with new analytical methods to determine how critical processes behave under the wide range of conditions that may develop as a consequence of global change. Only with this new knowledge can science provide the information society needs to adapt to a changing global environment.

Spatial and temporal heterogeneity

A basic tenet of experimental science is to eliminate all sources of variance except the experimental treatment in order to develop predictive models based on cause and effect relationships. However, in the real world environmental conditions are continually fluctuating over time, and often change significantly over short spatial distances. This heterogeneity complicates the design of relevant ecosystem experiments, and presents a major challenge for both measuring and modeling ecosystem processes over the heterogeneity of natural landscapes. Variation in topography, geology, soils, and microclimate influences processes that often have nonlinear dynamics, making accurate estimates of fluxes or processes at large scales extremely difficult. Much of the critical heterogeneity occurs at spatial scales smaller than those detected by most satellite sensors.

Furthermore, the relevant spatial and temporal heterogeneity typically changes as environmental conditions change. For example, a two-degree change in mean temperature may have little impact in a system that averages 20°C or -10°C, but likely will have a huge impact in a system that averages 0°C. A better understanding of the effect of environmental heterogeneity on ecosystem processes, as well as better methods for quantifying heterogeneity, are essential for making accurate predictions of how ecosystem processes will respond to global change. New statistical and mathematical approaches for understanding the relative importance of multiple interacting factors are essential. These issues are important in virtually all ecosystems, both terrestrial and aquatic.

‘Scaling up’ from observations to integrated quantitative understanding of heterogeneous ecological systems is an important scientific challenge. Consider, for example, forest canopies and their role in regulating exchanges of matter and energy with the atmosphere. It is not yet clear how to quantify the effects of spatial and temporal heterogeneity on canopy exchange. A further example comes from oceanic ecosystems. Many processes (e.g., larval dispersal) that are critical to the maintenance of valuable coastal fisheries occur at scales much larger than have ever been studied. Can small-scale studies inform management of fisheries, or must experiments be completed at the scale of entire marine ecosystems? Models need further development to include the many cross-scale dynamics. Effects of land use, water use, and disturbance histories on controls of energy and water feedback to the atmosphere also need further study. The basic principles of the scaling rules to better estimate the flux exchange of the land surface to the atmosphere need to be improved.

Section 5

PRIORITY ECOSYSTEMS

Many workshop participants were supportive of the idea that CCSP ecosystem research should focus on priority ecosystems that are (a) economically important and/or (b) likely to experience abrupt environmental changes or threshold effects. Much of the workshop discussion about priority ecosystems focused on arctic, coastal, and dryland systems. Within each of these systems there are important subsystems (e.g., forests, wetlands, and headwaters) that merit special attention because of their critical roles in whole-system resilience and feedbacks to climate change.

Arctic ecosystems

Predicted temperature increases are largest in high northern latitudes. Arctic ecosystems are sensitive to climate change, contain large stores of carbon in frozen soil that could be released to the atmosphere, and may play other key roles in ecosystem feedbacks to climate (e.g., changes in albedo or biogenic emissions of aerosol-forming gases). An integrated program of investigations in arctic ecosystems is needed to better define the current and potential effects of climate warming on: (a) albedo (vegetation, snow cover, sea ice); (b) vegetation dynamics; (c) soil organisms; (d) aquatic ecosystem processes (e.g., spring algal blooms) mediated by ice-edge melt rates; (e) ecosystem disturbance mediated by insects, disease organisms, and fire; (f) sources/sinks of greenhouse gases; and (g) animal species and communities adapted to arctic climate conditions (Figure 12).



Figure 12. Researcher collecting Antarctic ice core samples for analysis of physical properties and resident biotic communities. Photo: Rodger Harvey.

Coastal ecosystems and their tributaries

Coastal regions support roughly half of the U.S. population and are sensitive to climate change effects. There may be substantial increases in sea level in some regions due to the thermal expansion of ocean water and an influx of freshwater to oceans from melting glaciers and ice, with the magnitude and rate of change varying locally, depending on tidal patterns and coastal morphology. Moreover, climate change and development may interact to affect the magnitude and timing of freshwater flows from inland watersheds into coastal zones. Further, biogeochemical processes in freshwater tributaries have a profound influence, not only on freshwater ecosystems and water quality, but on the flux of materials to

coastal waters. Future scenarios of land use change may exacerbate the impacts of climate change on nutrient and material transformations.

Sea level rise and changes in freshwater inflows could affect many aspects of coastal ecosystems, including: the frequency and severity of flooding and storm surge events; drinking water supplies; agriculture and forestry operations; residential, industrial, transportation, and recreational infrastructure; pollutant loads to estuaries and associated wetlands; coral reef ecosystems; and populations of fish and other species that depend on the estuaries, coral reefs, and other coastal ecosystems. Further, since headwaters and coastal wetlands are critical habitats for many species and are critical regions for material transformation (e.g., nitrogen uptake), impacts to these systems could have far-reaching effects on freshwater quality, coastal water quality, and fisheries.

At present, we have only a broad understanding of what may happen across broad areas. We need to know far more about expected impacts for specific regions (i.e., at scales that are relevant to managers and planners), particularly impacts associated with interactive effects of temperature, water level, and freshwater inflow from upland areas. We also need information on adaptation strategies.

Dryland ecosystems

Expanding human populations in the arid and semi-arid regions of the western United States are placing considerable stress on aquatic and terrestrial ecosystems. At the same time, many dry forest ecosystems in the west are at high risk of uncharacteristic wildfire due to combinations of fire suppression, insect outbreaks, and other factors. There is some evidence that climatic conditions were relatively wet in much of the western United States during the 20th century. A return to drier conditions could have profound effects on human populations and the ecosystems they manage for drinking water, agricultural production, and recreation. This is particularly important where groundwater extractions and inter-basin transfers of water are leading to the degradation of aquatic and terrestrial ecosystems (Figure 13).



Figure 13. These photos show the massive die-off of pinyon pines (*Pinus edulis*) that occurred across more than two million acres of the southwestern U.S. during a recent drought, exacerbated by unusual warmth (Breshears et al. 2005).

SUMMARY

We have made substantial advances in our understanding of ecosystems in relation to global changes since programs were first formulated toward this goal two decades ago. However, with the rates of change in global change drivers that we are seeing, and the complex interactions that are being set in motion (which include nonlinearities and surprises), we have a large research challenge yet before us.

APPENDIX 1

A SHORT HISTORY OF ECOSYSTEMS RESEARCH ON GLOBAL CHANGE

A. Introduction

Society has been long concerned with the major impacts of human activities on natural systems, both locally as well as globally, as was chronicled by Marsh over a century ago (Marsh 1865), and more recently by Turner *et al.* (1990) and Vitousek *et al.* (1997), among legions of other observers.

However, it has only been in the past two decades that these concerns have been put into an Earth System Science context and related to global change. One thread of the development of new understanding and approaches can be seen in the publications of the U.S. National Research Council (NRC) and the International Geosphere Biosphere Program.

In 1986, the NRC presented a proposal for the initial priorities for research on global change as a contribution to the emerging International Geosphere-Biosphere Program (NRC 1986). What kinds of priorities were set at this early stage in the development of the global change agenda related to ecosystems?

It was noted at that time that we needed to develop a global ecology to bridge the localized information that ecologists had traditionally collected and global-scale phenomena. For example, ecological information could not be linked then directly with atmospheric circulation models. It was noted also that, “there is no way to extrapolate point measurements of terrestrial CO₂ fluxes to global scales,” and therefore a whole new scale of research efforts was needed within the ecological community.

The 1986 NRC report went on to propose a research goal within this new field of global ecology of measuring global metabolism, a goal far beyond the capacity of researchers at that time. More specifically, the report called for the development of methods to examine production and decomposition processes, not only regionally but globally, integrating biogeochemical cycles with the climate system, and accounting for the additions and losses of species on global metabolism. Further goals outlined were related to making a global assessment of the extinction-invasion problem as well as the development of an experimental approach to ecosystem functioning. To accomplish the objective of moving ecology “upscale,” there was a call for the establishment of Biosphere Observatories that could provide information on metabolism at landscape scales.

These were very bold and important goals. How have we done in the interim? Progress in several specific areas is summarized in sections that follow this introduction. In broad outline, it is clear that we have made enormous strides toward the initial objectives. For example, the field of Earth System Science is now fairly well institutionalized. Academic programs, research centers and institutes, and research support for this general field are now very well established and substantial. Students can now earn degrees in Earth System Science at a number of universities.

Recently the Carnegie Institution of Washington established their first new department in 70 years—a Department of Global Ecology.

As a response to the criticisms that the US global change program was not focusing sufficiently on ecosystems, a report was produced by the National Research Council (NRC 1994), chaired by F. Stuart Chapin III. This report gave specific ecosystem research guidance for the developing Federal Global Change Research Program, which was first outlined in the FY 1990 U.S. Global Research Program (CES 1989).

The Chapin report suggested six specific research questions:

- 1) What are the interactive effects of changes in CO₂, climate and biogeochemistry on the terrestrial carbon cycle and on food and fiber production?
- 2) What factors control trace gas fluxes between terrestrial ecosystems and the atmosphere?
- 3) What are reasonable scenarios of the future distribution, structure, and productivity of both managed and unmanaged ecosystems based on changes in land use, disturbance regime, and climate?
- 4) How will global change alter biotic diversity and what are the ecosystem consequences?
- 5) How will global change affect interactions among biota and the hydrological cycle and surface energy balance?
- 6) How will global change affect biotic controls over transport of water, nutrients, and materials from land to freshwater ecosystems and to coastal zones of the ocean?

B. Measuring global metabolism

By the end of the 1980s, the tools for measuring global metabolism, from the top down, were in place. Early papers, such as the one by Heimann *et al.* (1989), illustrated how information on seasonal trends of atmospheric CO₂ could be coupled with atmospheric circulation patterns and remotely sensed images (NDVI). Since that time, there has been an enormous flood of papers based on innovations that have permitted us to view the seasonal primary productivity of the Earth and its effects on the composition of the atmosphere (e.g., Field *et al.* 1998).

There are now efforts underway to measure ecosystem metabolism using a bottom-up approach, i.e., by integrating measurements of gas fluxes for specific ecosystems. Large gas flux networks are now operational in the U.S. and in Europe (Baldocchi *et al.* 2001), and the numbers of stations are growing. Although these allow detailed measures of the gas fluxes of specific ecosystems, and of whole ecosystem metabolism, a very dense network is required to make regional generalizations. Further, the existing networks do not span all major ecosystem types, including some critical to the provision of ecosystem services.

Flux towers that extend to very large heights (400 m vs. the average 30 m towers for forest flux measurements), in combination with light aircraft, are now being utilized to assess more regional landscape gas exchange patterns (footprint of 500 km) rather than ecosystem-specific fluxes (Helliker *et al.*, 2004). It is interesting to note that the vision given for biosphere observatories in 1986 (NRC 1986) was precisely that which is now in the early stages of development as exemplified by the Helliker paper (Ibid).

The combination of information from both types of flux systems (small and large scale) should move us further along in our understanding of both ecosystem and regional exchanges of gases, and hence carbon and water exchange.

Thus the last couple of decades have certainly provided the tools to measure ecosystem metabolism—that is, the temporal exchanges of carbon, energy, and water between vegetation and the atmosphere. How about links with the climate system?

C. Linking biogeochemistry and the climate system

One of the innovations associated with development of the Earth System paradigm (NASA 1988) was conceptually linking biogeochemistry and the Earth's climate system. Quantifying the influences of processes in the ocean and on the land on climate was an enormous challenge because of the differences in scale that existed at that time between ecological and climate research. Mooney *et al.* (1987) illustrated how vegetation and soils were involved in gas emissions that had an impact on climate. By the early 1990s, the first process-based models were developed that linked global patterns of primary production, decomposition, and nitrogen cycling (Melillo *et al.* 1993). Other models utilized remote sensing to achieve the same objective (Potter *et al.* 1993). These same approaches permitted the evaluation of the consequences of land use change on the Earth's productive capacity (DeFries *et al.* 1999).

For shorter time-scales, Sellers *et al.* (1997) were able to link energy, water, and carbon exchanges of land surface interactively with global circulation models, and further to show convincingly that physiological characteristics of the vegetation had important feedbacks to the climate system (Sellers 1996). As an example of approaches to viewing climate/vegetation interactions on a more historical scale, Foley *et al.* (2003) have shown how climate shifts interact with vegetation feedbacks on climate to reinforce the new vegetation state. Thus global change research had early achievements in fulfilling some of the very initial goals of the program, and recent work continues to build on these principles.

Again, then, important advances were made in relating longer-term biogeochemical processes with the shorter-term physiological processes that link directly to the climate system.

D. The oceans

The initial effort on oceans and global change was focused on biogeochemistry, principally the carbon cycle, in one of the largest multi-disciplinary studies of the oceans ever undertaken

(JGOFS). The results of this 15-year program have recently been summarized (Fasham 2003). Very important new findings on oceanic carbon cycling are still arising (Feely *et al.* 2004). Subsequent multinational global change ocean research has been centered on the Global Ocean Ecosystems program (GLOBEC) with a focus on how global climate change may affect the abundance and production of animals in the sea (Fogarty and Powell 2001). A major emphasis of the research is to understand the coupled bio-physical responses of marine ecosystems to climate change. This program consists of US national efforts on both coasts and a program in the Southern Ocean, as well as involvement with an international effort. Overall, the GLOBEC program is in a synthesis stage, and the results can serve as a springboard for CCSP efforts in marine systems.

E. What about species composition?

The challenge that was laid down in 1986 was to develop an understanding of how biodiversity was affecting Earth system processes. This was a big challenge for two reasons. First, biodiversity/environment interactions were generally studied at small scales. Second, basic understanding of the link between diversity and ecosystem processes was generally lacking. Again the ecological community rose to this challenge and initiated a large international effort to gather information on these relationships. Finding direct data unavailable, a whole series of experiments were initiated across the globe to test these relationships (Loreau *et al.* 2001). This work is still ongoing with new innovative experimental approaches being utilized (Diaz *et al.* 2003). Although the scientific underpinnings of diversity/ecosystem functioning relationships are being clarified, new approaches are still needed and more relationships need to be explored. Further, better links need to be made with Earth System models. Finally, as called for in the initial 1986 NAS program statement, more attention needs to be focused on the consequences of species additions (invasive species) to ecosystem functioning and feedbacks (see Sax and Gaines 2003), as well as to the impacts of global changes on the invasion process (Mooney and Hobbs 2000). The international program on biodiversity science, DIVERSITAS, has a number of ongoing programs directed toward the diversity/functioning relationship.

As a response to the challenges of 1986 (NRC 1986), the International Geosphere Biosphere Program (IGBP) was established with a number of programs explicitly focusing on the impacts of global change on ecosystems. One of these was GCTE, Global Change and Terrestrial Ecosystems (Steffan *et al.* 1992). The results of this effort were published in 1999 (Walker *et al.* 1999) and that of the whole IGBP in 2004 (Steffan *et al.* 2004). Some of these results are noted below.

F. Experiments on the impacts of interactive drivers of global change

Efforts to meet the goal of increasing our understanding of global change and ecosystems have been substantial in many ways. The GCTE established a global network of ecosystem-level experiments on responses to elevated CO₂ (Walker *et al.* 1999). The initial GCTE plans called for interactive experiments utilizing CO₂, warming, nutrients, and water manipulation. They also called for experiments on the major ecosystem types with priorities on tundra and savannah

ecosystems. Unfortunately, the technology and economic support were not sufficient to meet these original goals. Nonetheless, the global network was able to provide important evidence that the predictions from single organism experiments did not translate into findings at the system level. Not all ecosystems responded positively to CO₂ fertilization, and decomposition processes were not affected as predicted. It was found that belowground processes were key to understanding CO₂ effects. Experiments in these years were focused almost exclusively on herbaceous systems.

Only recently have experiments been conducted on interacting global change elements [CO₂ and ozone interactions (Percy *et al.* 2002); CO₂, warming, N deposition, and water augmentation on productivity (Shaw *et al.* 2002); and diversity (Zavaleta *et al.* 2003)]. The results indicate that these types of experiments must be carried out more widely in order to build a more sound predictive base for global change impacts on ecosystem functioning and distribution.

G. Trace gas fluxes from ecosystems

The IGBP initiated the International Global Atmospheric Chemistry program (IGAC) to better understand the drivers of trace gas emissions and the impact of these gases on the climate system. Through this program, and science progress in general, we have narrowed the uncertainty about the quantities of trace gas emissions as well as their sources. Estimates based on very few measurements have been considerably augmented by new measures on both land and over the ocean. Remote-sensing observations on the geographical extent of fire events and their seasonality have added a whole new dimension of analysis (Steffan *et al.* 2004). Intensive research programs have brought new knowledge, synthesis, and model formulations for predictions on neglected gases, such as biogenic hydrocarbons (Fuentes *et al.* 2002). Importantly, these programs have brought atmospheric scientists working together with ecologists.

H. Global change drivers of impacts on ecosystem distribution and production

Substantial progress was made early in global change research to move beyond simple models that showed ecosystems moving as units with the changing climate and information on the role of other global change drivers. Integrated global models were developed early on that had interacting drivers as well as impacts (Rotmans *et al.* 1990). The integrated IMAGE model is now in version 2.1 (Alcamo *et al.* 1998), and uses social drivers as well as biophysical ones to predict energy demand and land use changes, and in turn, atmospheric gas concentrations, climate, new land use, and managed and unmanaged ecosystem impacts. This model has been used extensively in assessments including the IPCC and the Millennium Ecosystem Assessment.

Additionally, there is now a whole new class of models that make predictions of biogeographical responses to global changes based on species' functional types rather than on biome abstractions (Prentice *et al.* 1992; Woodward *et al.* 1995; Neilson 1995; Foley *et al.* 1996). Some of these

models have already been utilized in national assessments of the potential impacts of global changes on ecosystem performance and distribution.

Curiously, the original research demand for models that would encompass the whole earth system is now being changed; more regional and local models are being called for as more national impact and response plans are being developed.

I. Global change impacts on biodiversity

Although early research activity focused on the impacts of species changes, as discussed above, there was less focus on the impacts of global change drivers on biodiversity. The first serious comprehensive effort on this topic was not published until this decade (Sala *et al.* 2000). There have been, however, extensive earlier efforts looking at the effect of habitat reduction on species diversity loss as well as the impact of the loss of megafauna through over-hunting (Dirzo and Miranda 1991). There are now solid analyses of the impact of climate warming on species' ranges (Parmesan and Yohe 2003), and there has been extensive development of increasingly sophisticated vegetation models for predicting the impact of climate change on biome shifts (Foley *et al.* 2000, Neilson *et al.* 1998).

J. Effects of vegetation change on large-scale hydrology

The interaction of the vegetation with the atmosphere has been addressed explicitly through an IGBP program on the Biospheric Aspects of the Hydrological Cycle (BHAC) (Hutjes *et al.* 1998, Kabat *et al.* 2004). The work of this program focused on local land-surface interactions with the atmosphere and how these interactions in turn influence global climate patterns. There are now suggestions that land use changes that influence surface albedo result in energy balance changes that influence climate-forcing equally to that of greenhouse gases (Pielke *et al.* 2002). There have been numerous studies showing the impact of tropical deforestation on local and regional climates (Lawton *et al.* 2001, Lean and Warrilow 1989, Zhao and Pitman 2002).

In spite of advances in our understanding of land surface/climate interactions, we still have done poorly in achieving the 1986 NAS global change priority setting exercise (NRC 1986) where, as one example, there was a call for a practical global observing system for soil moisture measurements. We are still not there, nor particularly close, although there has been continuing exploration and promise of satellite measurements to accomplish this task.

K. Global change effects on biotic controls on land-water interactions

Although the IGBP had a focused research program on land/water interactions, it was limited principally to the coastal zone (Land-Ocean Interactions in the Coastal Zone – LOICZ). We have learned much about the increasing influence of land-based human activities on the coastal waters, including those factors leading to the formation of hypoxia zones (Diaz 2001, Grantham *et al.* 2004). We have uncovered subtle interactions between animal populations on land and the

sea, and how changing climatic conditions can greatly influence these interactions (Velarde *et al.* 2004).

Rivers and lakes, and their interaction with the land, were not a central focus of the ecosystem program of the IGBP. However, considerable progress has been made in advancing our knowledge of the enormous extent of human physical alteration of the Earth's 'plumbing system' (Dynesius and Nilsson 1994), the growing extent of human appropriation of the available water (Postel *et al.* 1996), and of the massive influence of humans on the biogeochemistry of waterways of the United States (Howarth *et al.* 2002). Yet, a far better understanding of the interactive effects of climate change, land use change, and water extractions is required if we are to prepare for global change, particularly in highly populated areas.

APPENDIX 2

AGENDA—U.S. CLIMATE CHANGE SCIENCE PROGRAM (CCSP) ECOSYSTEMS WORKSHOP, FEBRUARY 23–25, 2004, SILVER SPRING, MARYLAND

| Monday, February 23, 2004 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| 7:00 a.m. – 8:00 a.m. (Council Room) | | Meeting with Ecosystems Interagency Working Group and Moderators | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7:15 a.m. (Outside the Maryland Ballroom) | | Registration and Continental Breakfast | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8:30 a.m. – 9:45 a.m. (Maryland Ballroom) | | Plenary Session <ul style="list-style-type: none">Bryce Stokes, Welcome & OverviewHal Mooney, Purpose and Outcome of WorkshopSusan Herrod Julius, CCSP Strategic PlanAl Lucier, Overview of Meeting SessionsJeff Amthor, Intro to First Day and Logistics | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9:45 a.m. – 10:00 a.m. (Maryland Ballroom) | | Break | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10:00 a.m. – 1:15 p.m. The goal of this session is to elicit and compile Priority Science Questions (PSQs) from each expert based on the broad direction given in the Ecosystems Chapter of the CCSP Strategic Plan. The 3 areas of research in the Chapter are: <ul style="list-style-type: none">Feedbacks between the ecological systems and global change, and their quantitative relationshipsPotential consequences of global change for ecological systemsOptions for sustaining and improving ecological systems and related goods and services, given projected global changes | | Breakout 1: Priority Science Questions for each of the Three Overarching Questions (INCLUDES WORKING LUNCH) Breakout Groups and Moderators: <table><tr><th>Question</th><th>Group</th><th>Moderator</th><th>Room</th></tr><tr><td>1</td><td>1</td><td>Nadelhoffer</td><td>Assembly</td></tr><tr><td>1</td><td>2</td><td>Ojima</td><td>Suite “A”</td></tr><tr><td>1</td><td>3</td><td>Running</td><td>Severn</td></tr><tr><td>2</td><td>1</td><td>Baron</td><td>Maryland (front)</td></tr><tr><td>2</td><td>2</td><td>Twilley</td><td>Maryland (back)</td></tr><tr><td>2</td><td>3</td><td>Band</td><td>Annapolis</td></tr><tr><td>3</td><td>1</td><td>Goldstein</td><td>Council</td></tr><tr><td>3</td><td>2</td><td>Huston</td><td>Suite “B”</td></tr></table> | | Question | Group | Moderator | Room | 1 | 1 | Nadelhoffer | Assembly | 1 | 2 | Ojima | Suite “A” | 1 | 3 | Running | Severn | 2 | 1 | Baron | Maryland (front) | 2 | 2 | Twilley | Maryland (back) | 2 | 3 | Band | Annapolis | 3 | 1 | Goldstein | Council | 3 | 2 | Huston | Suite “B” |
| Question | Group | Moderator | Room | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 | Nadelhoffer | Assembly | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 2 | Ojima | Suite “A” | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 3 | Running | Severn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 1 | Baron | Maryland (front) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 2 | Twilley | Maryland (back) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 3 | Band | Annapolis | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 1 | Goldstein | Council | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 2 | Huston | Suite “B” | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1:15 p.m. – 1:30 p.m. | | Move to Overarching Question Plenary Sessions | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

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| 1:30 p.m. – 3:15 p.m. <i>Discuss and consolidate Priority Science Questions (PSQs) from breakouts, relative to each Overarching Question.</i> | <i>Concurrent Plenary 1: Overarching Questions</i> <i>Question 1 – Assembly Room: Francisco Chavez, Moderator</i> <i>Question 2 – Maryland Ballroom: Margaret Palmer and Hal Mooney, Moderators</i> <i>Question 3 – Council Room: Al Lucier, Moderator</i> |
| 3:15 p.m. – 3:30 p.m. (Maryland Ballroom) | <i>Break</i> |
| 3:30 p.m. – 5:00 p.m. (Maryland Ballroom) <i>Report-out of PSQs relative to each Overarching Question</i> | <i>Full Plenary</i> <ul style="list-style-type: none"> ▪ Hal Mooney, Moderator ▪ <i>Question 1 Presenter: Francisco Chavez</i> ▪ <i>Question 2 Presenter: Margaret Palmer</i> ▪ <i>Question 3 Presenter: Al Lucier</i> |
| 5:15 p.m. – 7:30 p.m. (Council Room) | <i>Workshop Steering Committee Meeting with Moderators and Ecosystems Interagency Working Group</i> |

Tuesday, February 24, 2004

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| 7:30 a.m. – 8:30 a.m. (Maryland Ballroom) | <i>Continental Breakfast</i> |
| 8:30 a.m. – 9:00 a.m. (Maryland Ballroom) | <i>Introduction to the Day</i> <ul style="list-style-type: none"> ▪ Bryce Stokes, Moderator |
| 9:00 a.m. – 9:15 a.m. | <i>Move to Breakout Groups</i> |

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| <p>9:15 a.m. – 11:45 a.m.</p> <p><i>Discussion of research approaches for high-priority research under each Overarching Question</i></p> | <p><i>Breakout Session 2: Research Approaches to Priority Science Questions (PSQs)</i></p> <p>Breakout Groups and Moderators:</p> <table><tr><td><u>Group</u></td><td><u>Moderator</u></td><td><u>Room</u></td></tr><tr><td>A</td><td>Nadelhoffer</td><td>Assembly</td></tr><tr><td>B</td><td>Ojima</td><td>Suite “A”</td></tr><tr><td>C</td><td>Running</td><td>Severn</td></tr><tr><td>D</td><td>Baron</td><td>Maryland (front)</td></tr><tr><td>E</td><td>Twilley</td><td>Maryland (back)</td></tr><tr><td>F</td><td>Band</td><td>Annapolis</td></tr><tr><td>G</td><td>Goldstein</td><td>Council</td></tr><tr><td>H</td><td>Huston</td><td>Suite “B”</td></tr></table> | <u>Group</u> | <u>Moderator</u> | <u>Room</u> | A | Nadelhoffer | Assembly | B | Ojima | Suite “A” | C | Running | Severn | D | Baron | Maryland (front) | E | Twilley | Maryland (back) | F | Band | Annapolis | G | Goldstein | Council | H | Huston | Suite “B” |
| <u>Group</u> | <u>Moderator</u> | <u>Room</u> | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | Nadelhoffer | Assembly | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| H | Huston | Suite “B” | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <p>11:45 a.m. – 12:15 p.m. (Maryland Ballroom)</p> | <p><i>Break and Pick Up Lunch</i></p> | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <p>12:15 p.m. – 1:30 p.m.</p> | <p><i>Working Lunch – Breakout Session 2 Continues</i></p> <p>Breakout Groups and Moderators:</p> <table><tr><td><u>Group</u></td><td><u>Moderator</u></td><td><u>Room</u></td></tr><tr><td>A</td><td>Nadelhoffer</td><td>Assembly</td></tr><tr><td>B</td><td>Ojima</td><td>Suite “A”</td></tr><tr><td>C</td><td>Running</td><td>Severn</td></tr><tr><td>D</td><td>Baron</td><td>Maryland (front)</td></tr><tr><td>E</td><td>Twilley</td><td>Maryland (back)</td></tr><tr><td>F</td><td>Band</td><td>Annapolis</td></tr><tr><td>G</td><td>Goldstein</td><td>Council</td></tr><tr><td>H</td><td>Huston</td><td>Suite “B”</td></tr></table> | <u>Group</u> | <u>Moderator</u> | <u>Room</u> | A | Nadelhoffer | Assembly | B | Ojima | Suite “A” | C | Running | Severn | D | Baron | Maryland (front) | E | Twilley | Maryland (back) | F | Band | Annapolis | G | Goldstein | Council | H | Huston | Suite “B” |
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| <p>1:30 p.m. – 1:45 p.m. (Maryland Ballroom)</p> | <p><i>Break</i></p> | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <p>1:45 p.m. – 4:30 p.m.</p> <p><i>Report-out for Breakout 2, relative to each Overarching Question</i></p> | <p><i>Concurrent Plenary 2: Overarching Questions</i></p> <p><i>Question 1 – Assembly Room: Francisco Chavez, Moderator</i></p> <p><i>Question 2 – Maryland Ballroom: Margaret Palmer and Hal Mooney, Moderators</i></p> <p><i>Question 3 – Council Room: Al Lucier, Moderator</i></p> | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <p>5:00 p.m. – 7:00 p.m. (Maryland Ballroom)</p> | <p><i>Reception</i></p> | | | | | | | | | | | | | | | | | | | | | | | | | | | |

| Wednesday, February 25, 2004 | |
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| 7:00 a.m. – 8:00 a.m. (Maryland Ballroom) | <u>Continental Breakfast</u> |
| 8:15 a.m. – 10:45 a.m. (Maryland Ballroom) <i>Report-out from each Overarching Question's session on research approaches and full discussion</i> | <i>Full Plenary</i> <ul style="list-style-type: none"> ▪ Margaret Palmer, Moderator Groups: <ul style="list-style-type: none"> ▪ Francisco Chavez, Question 1 Reporter ▪ Hal Mooney, Question 2 Reporter ▪ Al Lucier, Question 3 Reporter |
| 10:45a.m. – 11:00 a.m. (Maryland Ballroom) | <i>Discussion of Next Steps by the Workshop Steering Committee</i> <ul style="list-style-type: none"> ▪ Al Lucier, Presenter |
| 11:00a.m. – 11:30 a.m. (Maryland Ballroom) | Climate Change Science Program Perspective on the Future <ul style="list-style-type: none"> ▪ Ari Patrinos, Acting Director, CCSP, Presenter |
| 11:30 a.m. – 11:45 a.m. (Maryland Ballroom) <i>Susan and Bryce will give a few remarks regarding the workshop referencing their opening remarks, identifying how the workshop met their expectations before adjourning the meeting.</i> | <i>Wrap-up and Closing Comments</i> <ul style="list-style-type: none"> ▪ Susan Julius & Bryce Stokes, Presenters |
| Adjourn | |
| 1:00 p.m. – 5:00 p.m. (Council Room) <i>Writing teams are the Workshop Steering Committee and Breakout Session Moderators.</i> | <i>Writing Team Drafts Workshop Report</i> |

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APPENDIX 4

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Group 1

Francisco Chavez served as the group coordinator. Subgroup leaders were Knute Nadelhoffer, Dennis Ojima, and Steve Running. Serving as recorders were Ruth Defries, John Hom, Jim Gosz, and Gloria Rapalee.

Group 2

Margaret Palmer served as group coordinator. Subgroup leaders were Jill Barron, Bob Twilley, and Michael Houston. Serving as recorders were Evan Delucia, Tom Gower, and Patrick Mulholland.

Group 3

Alan Lucier served as the group coordinator. Subgroup leaders were Larry Band and Robert Goldstein. Serving as recorders were Linda Heath and Tony Janetos.

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